

The KHOLOD Experiment: A Search for a New Population of Radio Sources

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Published data from long-term observations of a strip of sky at declination $\delta \sim 5^\circ$ carried out at 7.6 cm on the RATAN-600 radio telescope are used to estimate some statistical properties of radio sources. Limits on the sensitivity of the survey due to noise imposed by background sources, which dominates the radiometer sensitivity, are refined. The vast majority of noise due to background sources is associated with known radio sources (for example, from the NVSS with a detection threshold of 2.3 mJy) with normal steep spectra ($\alpha = 0.7 - 0.8, S \propto \nu^{-\alpha}$), which have also been detected in new deep surveys at decimeter wavelengths. When all such objects are removed from the observational data, this leaves another noise component that is observed to be roughly identical in independent groups of observations. We suggest this represents a new population of radio sources that are not present in known catalogs at the 0.6 mJy level at 7.6 cm. The studied redshift dependence of the number of steep-spectrum objects shows that the sensitivity of our survey is sufficient to detect powerful FR II radio sources at any redshift, right to the epoch of formation of the first galaxies. The inferred new population is most likely associated with low-luminosity objects at redshifts $z < 1$. In spite of the appearance of new means of carrying out direct studies of distant galaxies, searches for objects with very high redshifts among steep and ultra-steep spectrum radio sources remains an effective method for studying the early Universe.

1. INTRODUCTION

The RATAN-600 radio telescope was initially proposed as a supplementary instrument to ordinary reflecting radio telescopes (paraboloids), in the form of a multi-frequency transit telescope suitable for surveys, with a fairly large daily field of view and resolution higher than a paraboloid of the same area. There are virtually no survey instruments operating at centimeter wavelengths. The reason is essentially that the vast

majority of background radio sources have spectra that fall off roughly linearly with decreasing wavelength. The field of view of a radio telescope falls off in proportion to the square of the wavelength; the time for a radio source to pass through the telescope beam also falls off with decreasing wavelength. All this means that nearly four orders of magnitude more time is required for a blind survey at centimeter than at decimeter wavelengths, of the same area of the sky and to the same depth in terms of background ra-

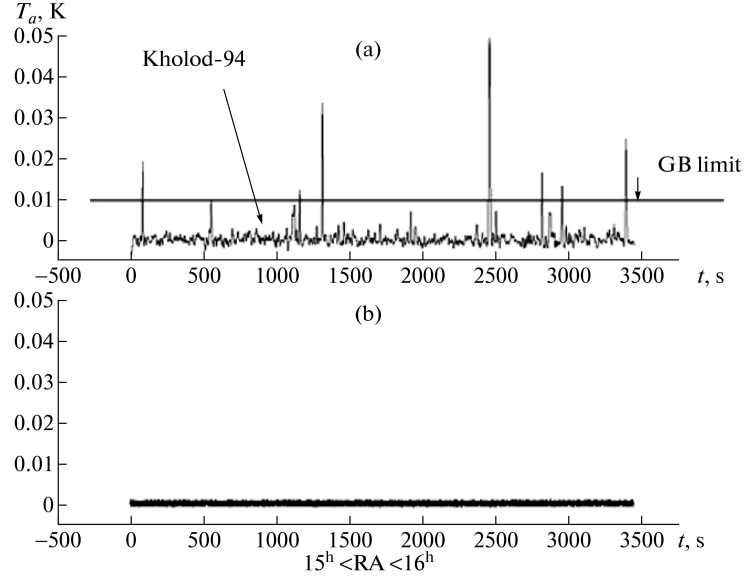


Figure 1. (a) Example of real noise taking into account background sources (the threshold for the GB6 catalog is shown). (b) Expected radiometer noise at the central wavelength of 7.6 cm for the KHOLOD experiment for monthly averaging of the data.

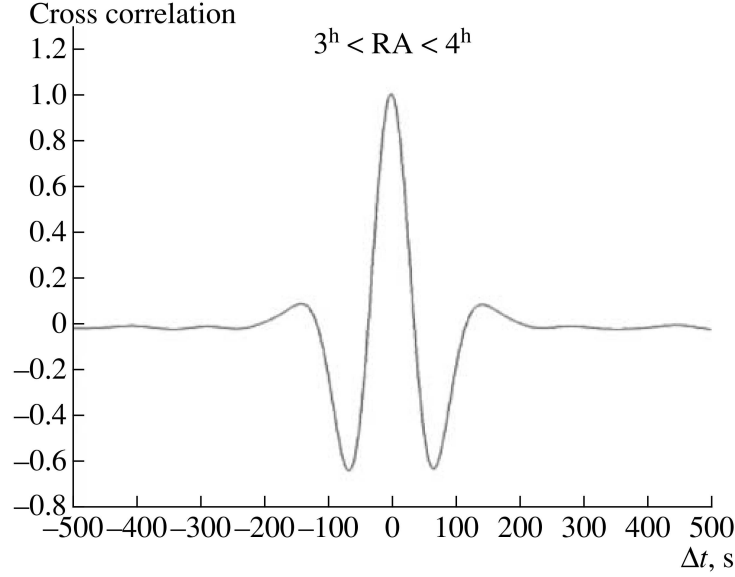


Figure 2. Cross correlation of two independent groups of observations in the KHOLOD-94 experiment ($\lambda = 7.6$ cm). The horizontal axis plots the time shift Δt between these groups of observations.

radio sources [1]. Deep surveys of large regions of the sky were begun on the RATAN-600 by radio astronomers of the Sternberg Astronomical Institute very soon after the completion of its construction. The short time for the passage of sources through the radio-telescope beam limited the sensitivity of the survey. The hope that sources with inverted spectra would dominate the centimeter-wavelength sky did not prove justified. The creation by the group of D.V. Korol'kov of a new generation of cryoradiometers with sensitivities appreciably higher than previous such instruments [2], as well as the decision not to try to survey large areas of the sky, was expected to enhance the depth of blind surveys. The appearance in the past 10 years of deep surveys a factor of 100 more sensitive than previous surveys cardinally changes the strategy used for blind surveys. Such surveys on the RATAN-600 telescope now yield virtually no new radio sources at centimeter wavelengths that are not present in the NVSS and FIRST catalogs at 21 cm. The only new radio sources that could appear in RATAN-600 observations but be absent from the NVSS catalog are objects whose maximum radiation occurs at centimeter wavelengths (for example, whose spectra display synchrotron self-absorption). There are few such objects, and for blind surveys of such objects, it is more effective to expand the survey area, rather than increase the depth of observations of a small survey region. Repeating observations of a single region increases the sensitivity as the square root

of the number of observations, while the dependence of the number of objects on flux density is nearly linear ($N \sim S^{-1}$) at centimeter wavelengths. Therefore, for a fixed total observing time, expanding the survey area provides a substantial gain in the number of new objects, compared to carrying out repeated observations of a single limited region.

The KHOLOD experiment (1980-2000) combined a survey of discrete radio sources with very deep studies of the anisotropy of the cosmic microwave background [3–7]. The sensitivity to the population of radio sources with normal steep spectra in this experiment was appreciably higher than the sensitivity of catalogs available at the beginning of the 1980s, and the vast majority of the objects detected were new. Only with the appearance of the Texas UTRAO new-generation 80-cm catalog¹ did it become possible to obtain a fairly deep sample of objects with steep and ultra-steep spectra. The curvature of the radio spectrum is one of the main indicators that can be used to identify candidate distant objects [8–10].

The “Big Trio” project, with the participation of three major facilities (RATAN-600, the VLA, and the 6-m telescope of the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences) [5, 11–38], was aimed at using this sample of sources to select candidate very distant galaxies. The sensitivity of the RATAN-600 was

¹ Kindly presented to us by Prof. J. Douglas prior to its publication.

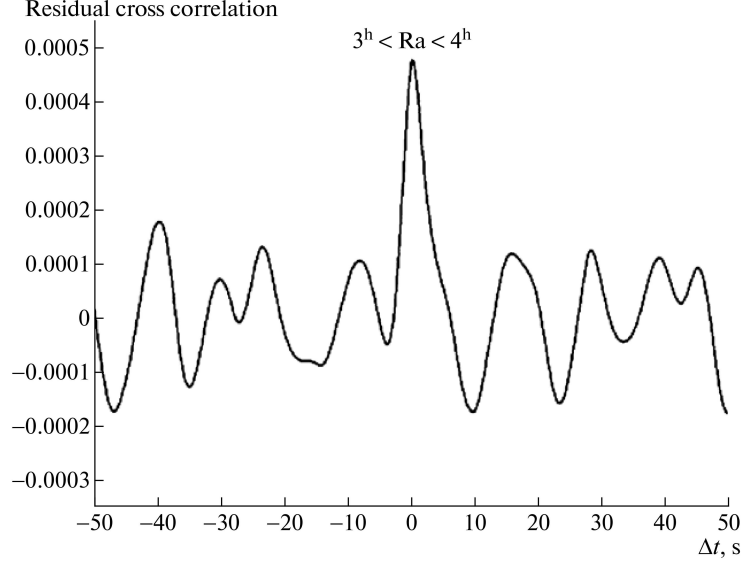


Figure 3. Noise due to background sources with flux densities less than 0.6 mJy for NVSS objects with normal steep spectra, which are clearly visible in the cross correlation of two independent sets of data, after filtration of the noise from all known NVSS sources.

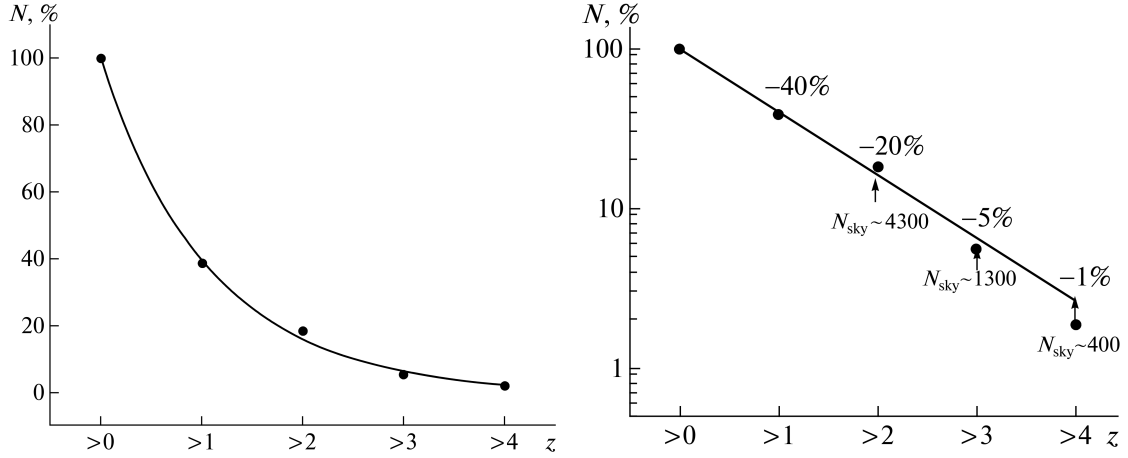


Figure 4. Left - drop in the number of radio sources with redshift according to data from the Big Trio project [38]. Right - estimate of the expected number of radio sources in the Universe with steep spectra as a function of redshift, based on the Big Trio data.

sufficient to detect powerful radio sources at all redshifts in blind surveys.

All these problems led to a simpler approach – observing radio sources at centimeter and millimeter wavelengths with prolonged integration

times, pointing a radio telescope at an NVSS or FIRST object. Unfortunately, even this method does not enable the construction of spectra of all the objects detected at decimeter wavelengths: sensitivities of several microjansky are required,

which is currently achievable only in very deep VLA surveys of very small areas of sky [39]. Blind surveys of such small areas provide important information about the properties of low luminosity radio sources and, as a rule, no new information about classical high-luminosity radio galaxies (FRI, FRII, QSR).

2. NOISE DUE TO BACKGROUND SOURCES

In the 1950s, the sensitivity of meter-wavelength radio telescopes was limited by noise due to background sources, and the hope was that this noise would be much smaller at centimeter wavelengths (proportional to the wavelength cubed [40]). Now, virtually the entire radio astronomy range is subject to noise due to background sources for observations with ordinary reflecting telescopes. Observations on the southern sector of RATAN-600 using its flat reflector encounter the same background-source noise limit as a paraboloid with the same surface area. In observations at medium and high hour angles using a single sector, the effective antenna beam is appreciably smaller than a paraboloid of the same area, and there is consequently less “confusion” noise.

Two-dimensional mapping at high hour angles applying reasonable data-reduction techniques enables reduction of the confusion noise by nearly an order of magnitude [41]. Even in one-dimensional surveys, optimal filtration of the

data yields almost the same results as filtration using two-dimensional maps. Even simple, ordinary, close two-beam scanning (the first derivative) substantially reduces the confusion noise. In the 1950s, Bracewell [42, 43] proposed to use the second derivative (“Cord Construction in Radio Astronomy”) to reduce the confusion noise.

This method proved to be very effective for the RATAN-600 beam at high hour angles. It leaves only noise from point-like radio sources that fall in a central strip of the survey half a beam wide in declination. However, with new-generation cryoradiometers, the confusion noise dominates the radiometer noise, even in modest cycles of observations. This is clear in the KHOLOD experiment: the expected radiometer noise at 7.6 cm for a monthly observing cycle is appreciably lower than the real noise (Fig. 1), and the correlation between the data for two small independent observing cycles is nearly 100%. Whereas all the sources detected were new in the first observations for the KHOLOD experiment in 1980, with the compilation of catalogs such as NVSS and FIRST, the detected objects now have counterparts in these deep surveys. The real confusion noise is clearly visible in a cross correlation of two independent groups of observations (Fig. 2): the shape of the curve corresponds fully to theoretical expectations in the absence of independent noise in the two sets of data. Confusion noise dominates, in spite of the filtration of noise due to background sources that are far from the beam axis using the “second

difference or derivative”, now called the Mexican Hat method [42, 44].

When the model (the NVSS objects extrapolated to 7.6 cm using a typical steep spectrum smoothed with the RATAN-600 beam) and observations are processed using a Mexican Hat filter to filter out background sources far from the beam axis, they display a high correlation. The Mexican Hat filter appreciably lowers the confusion noise, but there remains the high noise of the radiometer. To estimate the contribution to the confusion noise by a new population of sources that are not present in known catalogs, we removed from the 7.6-cm data all NVSS objects with flux densities close to their limiting value ($S_{lim} = 2.3 \text{ mJy}$ at 21 cm, which corresponds to $S_{lim} = 0.6 \text{ mJy}$ at 7.6 cm, assuming a typical steep spectrum).

Figure 3 presents the residual cross correlation (in arbitrary units) after removing all known features brighter than 0.6 mJy. Thus, all features distinguishable as individual sources can be identified with NVSS sources. There remains noise due to weak background sources at the sub-mJy level at 7.6 cm, which is fairly firmly detected statistically (via the cross correlation of independent data sets) in deep surveys such as KHOLOD (see also the circum-zenith survey described in [45, 46]). These sources are not detected in the NVSS catalog at 21 cm.

3. THE NATURE OF THE WEAK RADIO SOURCES

We show below that this new population of radio sources visible statistically in deep RATAN-600 surveys is most likely associated with low-luminosity objects. Useful information about the population of objects with high radio luminosities can be extracted from the Big Trio project. Photometric and spectral redshifts of objects with steep and ultra-steep spectra in the field of view of the KHOLOD experiment are presented in [38]. Redshifts could be determined for 54 of the 71 studied objects: of these ten have $z > 2$, three have $z > 3$, and one has $z > 4$ (RCJ 0311+0507, $z = 4.514$). Figure 4 (left) shows the drop in the number of radio sources with redshift for these 54 objects. Based on data published in 2007-2010 [38, 47–51], there are currently 194 known radio sources with $z > 2$, 47 with $z > 3$, and 9 with $z > 4$. It is possible to extrapolate these data to the entire sky, taking into account the KHOLOD survey region (0.005 ster; Fig. 4, right). Note that all powerful radio galaxies in the KHOLOD field of view were detected at the limiting flux level of the RC catalog of 5-10 mJy (the Big Trio project), right to the epoch of secondary reionization ($z = 10$). This can be seen in Fig. 5 (which shows a normalized curve for the radio-source counts at 21 cm [52]).

Powerful radio galaxies are believed to be associated with the activity of supermassive black holes at the centers of their giant elliptical host

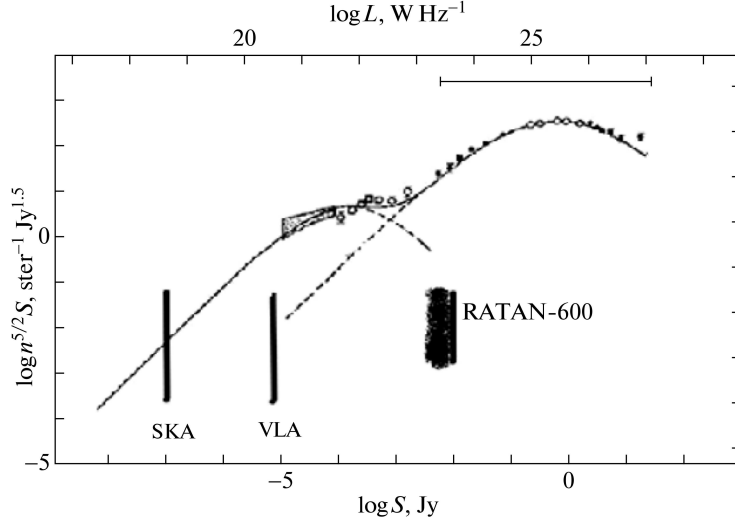


Figure 5. Estimate of the penetrating power of radio telescopes of various classes for studies of galaxies with various luminosities (dashed). The upper horizontal line marks the range occupied by flux densities of classical radio galaxies in the redshift range $0 < z < 8$, which encompasses the entire Universe to the epoch of reionization. The vertical lines show the limits attainable on the RATAN-600 and VLA and the expected limit for the Square Kilometer Array.

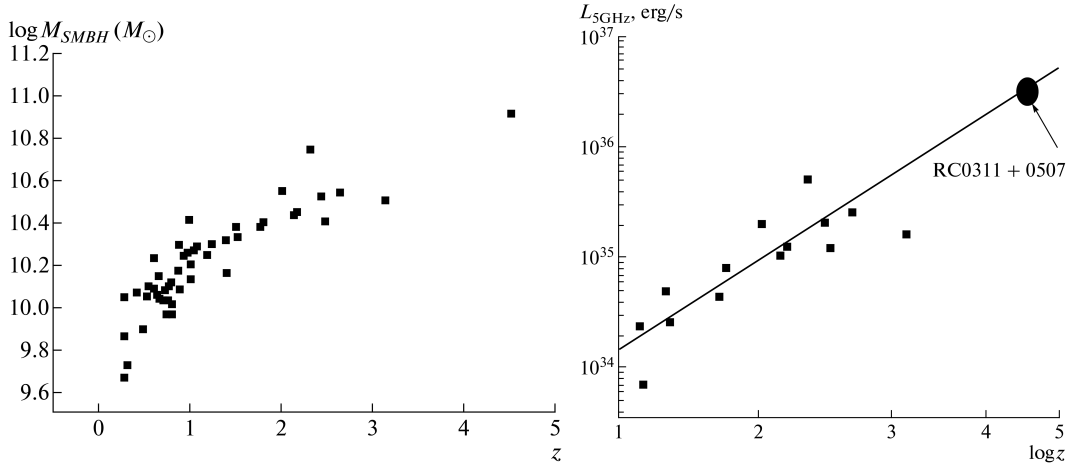


Figure 6. Left – masses of supermassive black holes detected in the KHOLOD field of view as a function of redshift for the population of steep and ultra-steep spectrum objects. The higher the redshift, the more massive the black holes required to explain their radio luminosities. Right – redshift dependence of the absolute 5-GHz luminosity for high-redshift FR II objects, based on the collected data of Miley and de Breuck [47]. The radio luminosity is proportional to $M_{SMBH}^{2.5}$, where M_{SMBH} is the mass of the supermassive black hole [53]. An object from the Big Trio project (RC J0311+0507) has the most massive black hole, according to [38].

galaxies. The Big Trio data can be used to estimate the redshift distribution of such galaxies in the Universe (Fig. 6, left). The Big Trio data are in agreement with recently published international data for radio sources with high redshifts (Fig. 6, right).

According to RATAN-600 data, the surface density of objects with high redshifts is much higher than the value detected in surveys of the entire sky, due to the lower limiting flux density of the KHOLOD experiment. It is important here that the statistical confusion noise is approximately equal to the flux density of radio sources whose surface density is about one per telescope beam [54]. In the KHOLOD survey, the effective beam size at 7.6 cm was about three square minutes of arc, which gives more than a million beams on the sky. The dependence of the number of FR II radio galaxies on the survey sensitivity estimated in [55] shows that, even with a sensitivity of 30 nJy at 21 cm, the surface density remains at about 50 sources per square degree, independent of the survey depth in the range 1 mJy-30 nJy. The number of antenna beams per square degree in the KHOLOD experiment (and the circum-zenith survey) is hundreds of times greater, supporting our conclusion concerning the low luminosities of objects in the “new population” of centimeter-wavelength radio sources. Their luminosities could be close to those of active spiral galaxies.

4. CONCLUSION (THE BIG TRIO PROJECT AND THE 21ST CENTURY)

The selection of candidate distant galaxies from among radio sources with ultra-steep spectra is an effective method for studying the early Universe in the 21st century. The vast majority of galaxies with $z > 1$ have been found using this method, although it remains unclear why objects with ultra-steep spectra have high radio luminosities. Powerful radio galaxies are accessible to observations with existing instruments at any redshift, right to the epoch of galaxy formation immediately after the end of the Dark Age ($z \sim 10$). Selecting ultra-steep-spectrum sources in radio surveys and following this up with optical studies of their host galaxies makes it possible to determine their redshifts and other properties. The Big Trio project was one of the first to use this approach. The penetrating ability of the RATAN-600 and SAO 6-m telescope are sufficient to confidently detect the population of FR II radio galaxies at high redshifts in the radio and measure the spectral properties of their host galaxies, as is illustrated by the example of the radio galaxy RC J0311+0507 (Figs. 7, 8).

The signal-to-noise ratio in this case is $S/N > 100$, the object’s flux densities are $S_{7.6\text{ cm}} = 135\text{ mJy}$ and $S_{21\text{ cm}} = 537\text{ mJy}$, its the largest angular size in the radio is 2.8, and its spectral index is $\alpha = 1.37$ [13, 25, 26, 36, 38]. Instrumental progress in all spectral ranges enables refinement of the role of this approach in

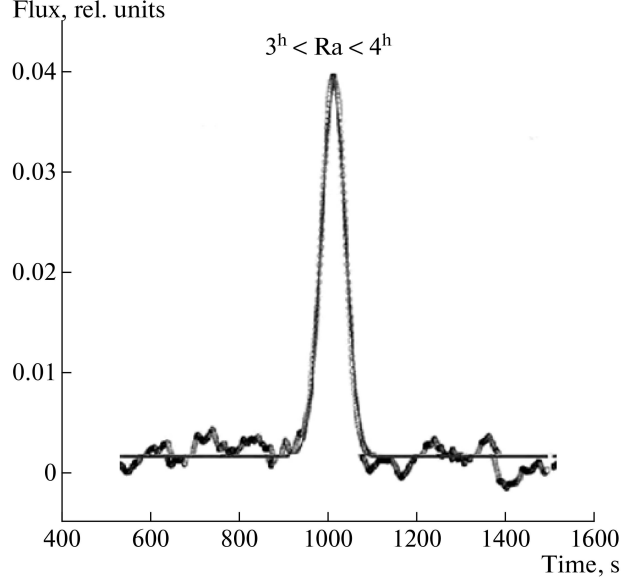


Figure 7. Individual scan of the radio source RC J0311+0507 at 7.6 cm (RATAN-600, 1980).

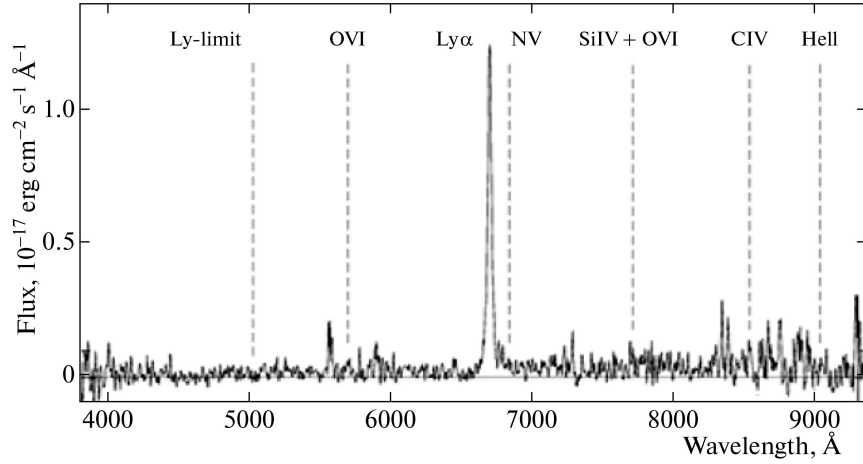


Figure 8. Optical spectrum of the host galaxy of RCJ 0311+0507 (2004) obtained using the SCORPIO spectrograph [56] mounted on the 6-m telescope of the Special Astrophysical Observatory.

current and future studies. Successful attempts to search for first-generation galaxies in deep optical and infrared ground-based and space-based observations have already been made. The use of gravitational lensing makes it possible to find candidate galaxies with redshifts $z = 7 - 9$, independent of their radio properties [57]. Nevertheless, we believe that behind searches for powerful radio sources lies the need to select galaxies with powerful active nuclei. It is current believed that

these could be indicators of the earliest clusters. The radio luminosities of galaxies are associated with activity of the supermassive black holes in their nuclei. It unexpectedly was found (in the Big Trio project) that, the higher the redshift, the higher the inferred black-hole masses. Moreover, theory predicts that the radio luminosity should depend on both the accretion rate and the rotational velocity of the black hole. It is believed that angular momentum can be transferred in collisions between galaxies or black holes. The accessibility of powerful FR II radio galaxies at any distance in the Universe to observations even with radio telescopes with only moderate sensitivities and their connection with first-generation

galaxies mean that these objects can be used to estimate deviations from the standard cosmology, by comparing the ages of the stellar populations of the host galaxies derived from multi-color photometry and the age of the Universe at the corresponding redshifts. Thus, radio and optical (infrared) selection supplement each other.

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